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Revisiting the HEC-18 Scour Equation

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Abstract

Accurate pier scour predictions are essential to the safe and efficient design of bridge crossings. Current practice uses empirical formulas largely derived from laboratory experiments to predict local scour depth around single-bridge piers. These formulas have two problems. First, they are hindered by scaling effects; second, they do not consider detailed hydrodynamic forces at work in the scour process. These formula deficiencies can often produce excessive over prediction of scour depths that can lead to unnecessary construction costs.

In an effort to improve the predictive capabilities of the HEC-18 scour model, this work uses field-scale data and nonlinear regression to develop a family of equations optimized for various non-cohesive soil conditions. Improving the predictive capabilities of well-accepted equations will save scarce project dollars without sacrificing safety. To help improve acceptance of modified equations, the familiar form of the HEC-18 equation is maintained. When compared to the HEC-18 local pier scour equation, this process reduced the mean square error of a validation data set while maintaining over prediction.

Introduction

The Federal Highway Administration defines scour as the result of the erosive action of flowing water, excavating and carrying away material from the bed and banks of streams and from around piers and abutments of bridges. The United States has approximately 600,000 bridges; about 80 percent require some sort of scour mitigation (Nassif *et al.* 2002). However, during the 40-year period ending in 2005, more than 1,500 bridges in the United States failed; nearly 60 percent of these failures were hydraulic in nature (Kornel Kerenyi, personal communication, June

18,2009). The cost of bridge failure or bridge closure far exceeds the cost associated with repair. Therefore, accurately determining scour depth while sizing foundations and waterway openings will help reduce costs over time (Richardson and Davis 2001).

An accurate determination of the expected scour at a bridge crossing is important for an economic and safe bridge design. Several models are available to predict the ultimate scour depth near piers or abutments (see Johnson (1995) or Muller and Wagner (2005) for lists of the most commonly used scour equations). Many factors, including the amount of cohesion in the sediment, or clear-water or live-bed conditions, determine the appropriateness of a particular model. Over the last several decades, models were developed, adjusted and improved. For example, Molinas (2003) adjusted the Colorado State University pier-scour equation to account for the coarse material fraction which is known as the K_4 adjustment factor in HEC-18 pier scour equation.

Laboratory data is the primary source of information used in model development. However, many authors note scale as a source of error in models derived from laboratory data (Hopkins and Vance 1980). These laboratory investigations typically model straight, rectangular channels with uniform approach-flow velocities, approach-flow depths, and non-cohesive bed material (Wagner *et al.* 2006). These characteristics rarely represent field conditions.

Most scour equations in common use today are empirically based. Scour is a complex process and accurate predictions are not likely to come from empirical models. However, empirical models are necessary since budgetary restrictions prevent the implementation of more complex, physics-based modeling for every bridge design. According to Mueller and Wagner, none of the commonly used scour equations accurately and conservatively (over) predict the scour observed in the field (Mueller and Wagner 2005). Inaccuracies exist for several reasons including a lack of hydrodynamic variables, laboratory source data and inaccuracy in field data measurements.

The goal of this work is to improve the HEC-18 local pier scour equation, Equation 1, in two ways. First, there is an attempt to improve the fit between predicted and observed scour by re-deriving the HEC-18 equation with field measurements of scour. Second, stratifying data based on approach depth ratio and creating a family of equations. These modifications are expected to lead to improved prediction performance largely because similarly grouped derivation data is expected to reduce variance in predicted scour depth ratios. Data is stratified based on the approach depth ratio, which in the HEC-18 equation is the pier width divided by the approach depth ratio. Due to data limitations in this study, the data is stratified into two sets only resulting in two unique predictive equations. However, the family of equations could expand as field-data collection programs grow and more data becomes available.

$$\frac{y_s}{y_1} = 2K_1K_2K_3K_4\left(\frac{a}{y_1}\right)^{0.65} Fr^{0.43} \quad (1)$$

Data

The National Bridge Scour Database, last updated in 2004 and maintained by the U.S. Geologic Survey, provided the data for the present analysis and provides data from 20 sites in eight states. Records were chosen for this analysis based on completeness. A record must contain enough data to apply the current version of the HEC-18 scour equation for use in this study. The database produced 148 records. However, due to a limited amount of complete data from cohesive soil, all data used in this investigation are from non-cohesive sites. Most records that met the completeness condition as described above had approach-depth ratios of less than 0.75 and Froude numbers less than 0.46 as shown in Figure 1.

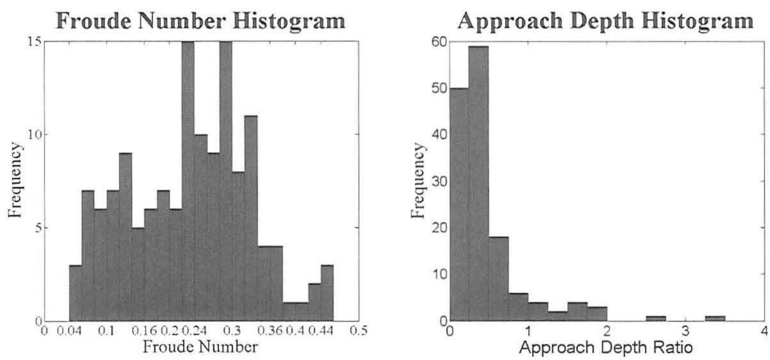

Figure 1: Approach depth ratios and Froude numbers of data for the combined derivation and validation data sets.

The first step in the data filtering process was to remove records with outlying relative scour depths, y_s/y_1. After removing the outliers, 145 records remained. The next step was to identify stratification points within the approach depth ratios. These break points are used to define the useful range of a particular equation in the family of equations being developed. Break points were determined by trial and error. These break points were selected as the largest group of data that would retain conservative prediction (i.e. predicted depths in excess of observed). Descriptive statistics used in the derivation of each equation in the family of curves are shown in Table 1 and Table 2.

The available field data was separated into a derivation data set and a validation data set. A single site may have many records, so validation data are chosen from two representative sites. No records from validation sites were also used for model derivation. This was done to ensure the new model could predict relative scour depths outside of the locations used to derive the equation (i.e., the equation was not relying on site-specific processes captured in the derivation process).

Table 1: Descriptive statistics used in deriving equation 2

Deriving Data Equation 2, lower range								
	flow depth (m)	velocity (m/s)	Froude number	scour depth (m)	relative scour depth	pier width (m)	approach depth ratio	median grain size (mm)
min	4.24	0.31	0.04	0.34	0.05	0.41	0.04	0.17
max	15.36	2.26	0.24	4.27	0.30	2.79	0.20	1
median	7.01	1.19	0.13	1.07	0.16	0.91	0.16	0.54

Table 2: Descriptive statistics used in deriving equation 2

Deriving Data Equation 2, upper range								
	flow depth (m)	velocity (m/s)	Froude number	scour depth (m)	relative scour depth	pier width (m)	approach depth ratio	median grain size (mm)
min	1.31	0.52	0.06	0.15	0.036	0.53	0.21	0.15
max	20.03	3.17	0.45	7.65	0.78	5.24	0.44	1.82
median	7.3	1.40	0.23	1.52	0.30	1.83	0.32	0.64

Regression

The HEC-18 equation was re-derived using nonlinear regression analysis. This process optimized parameters to a user-defined functional form. The resulting parameters minimize the error between predicted and observed values through an ordinary least-squares procedure. The functional form used in this analysis is the HEC-18 scour equation with an additive factor of safety, see Equation 2.

$$\frac{y_s}{y_1} = b_1 K \left(\frac{a}{y_1} \right)^{b_2} Fr^{\,b_3} + FOS \tag{2}$$

where y_s is the scour depth, "a" is the pier width, y_1 is the flow depth directly upstream of the pier and Fr is the Froude number, K is the correction factor (which embodies K_1 through K_4 of the HEC-18 equation) and was not modified, and each "b_i" is an optimized regression parameter. The independent variables are the approach depth ratio (a/y_1) and Froude number (Fr). Finally, FOS is the factor of safety.

The nonlinear regression described above yields a best-fit model that both under-and over predicts scour. A factor of safety is added to the best-fit equation in order to transform it into a design equation by ensuring all predictions exceed observations. The factor of safety is computed by examining the maximum under prediction from the deriving data set. This maximum under prediction was added to each predicted value in the validation set. Using an additive factor of safety as suggested in equation 1, an approach modeled after the Froehlich pier-scour design equation (Brunner 2008), increases the utility of the equation. A simple modification makes the equation appropriate for non-design applications.

The first equation developed in the family of equations uses a subset of the selected records where all approach depth ratios are less than 0.2. There are 21 data points in this deriving data set and 16 points in the validation data set. In the deriving data set, the Froude numbers ranged from 0.04 to 0.24, while in the validation data the range was 0.07 to 0.30.

The second equation in the family had approach depth ratios between 0.2 and less than 0.45. The deriving data set contained a total of 48 data points; the validation data set contained 18. The Froude number ranged from 0.06 to 0.45 in the deriving data set and from 0.04 to 0.44 in the validation data set as shown in Table 3. The approach depth ratios of the remaining 42 records are too sparse to produce a meaningful model and extend the family of equations beyond approach depth ratios of 0.45. However, with additional data the authors are optimistic the family of equations can continue to expand and cover a larger range of approach depth ratios.

Table 3: Froude numbers and regression parameters associated with each equation

	Froude Number		Regression Parameters			
	Deriving	Validation	b_1	b_2	b_3	FOS
Equation 2 lower	0.04 to 0.24	0.07 to 0.30	12.62	1.86	0.86	0.15
Equation 2 upper	0.06 to 0.45	0.04 to 0.44	1.23	2.90	-0.51	0.58

Results

The HEC-18 local pier-scour equation was derived across the entire range of available data with a one-size-fits-all approach. The error associated with the relative scour prediction increases linearly with the predicted relative scour depth (y_s/y_1) as shown in Figure 2. The one-size-fits-all approach leads to significant over prediction, especially at larger expected scour depths. This results from adjusting the model across the entire domain to ensure over prediction at a few hard-to-fit data points. The family of equations can accommodate hard-to-fit points as well, but does so without adjusting all values across the entire domain. This results in increasing or decreasing residual error depending on stratification points; however, all points remain over predicted, as shown in Figure 3.

Both lower and upper members of Equation 2 yield significant improvement in terms of mean square error when compared to predictions based on the original HEC-18 equation. Both equations still over-predict observed values of relative scour depth, but are significantly less than the original HEC-18 equation (Table 4 and Figure 3).

While any field-scale data is a welcome addition to the database, this work highlights the need for field-scale data with expected approach depth ratios between 0.45 and 1.25. Data with approach-depth ratios greater than 1.25, commonly referred to as wide-pier data, historically lacks representation in both laboratory and field-scale data sets. Should enough field-scale data become available to expand the family of equations to approach-depth ratios well beyond 1.25, wide piers will not require a special correction factor as is currently the case in Hydraulic Engineering Circular 18 (Richardson and Davis 2001).

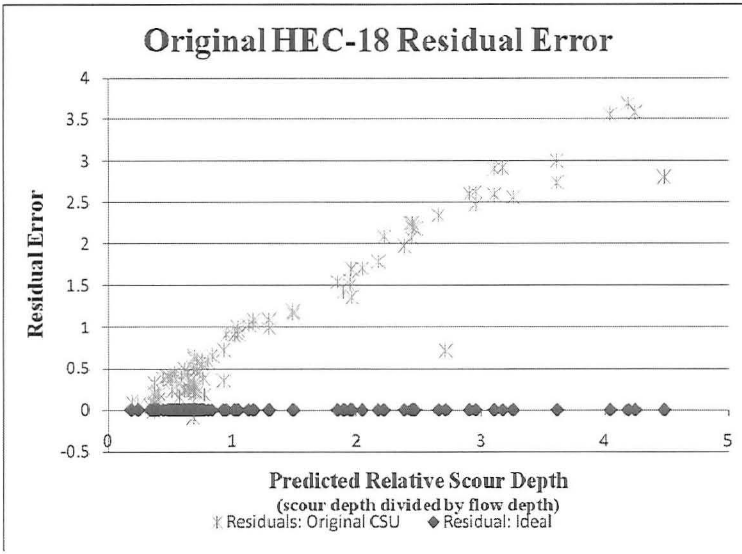

Figure 2: Residual error of the HEC-18 scour equation based on all available data.

A similar stratification analysis was also performed based on the Froude number. Initially, the same procedure as described above was implemented. Specifically, no restrictions were placed on the approach-depth ratios. However, due to the scarcity of data beyond an approach depth ratio of 0.75, favorable results were not obtained. Restricting data to approach depth ratios less than 0.75 yielded better results. With approach depth ratios restricted, the data were stratified based on Froude number. The first stratification point was a Froude number less than 0.25. All validation observations were over predicted but subsequent models could not over predict all of the observations in the validation data. The mean square error associated with the stratified Froude model is 0.07 on the deriving data set, while the mean square error associated with the original HEC-18 equation is 0.27.

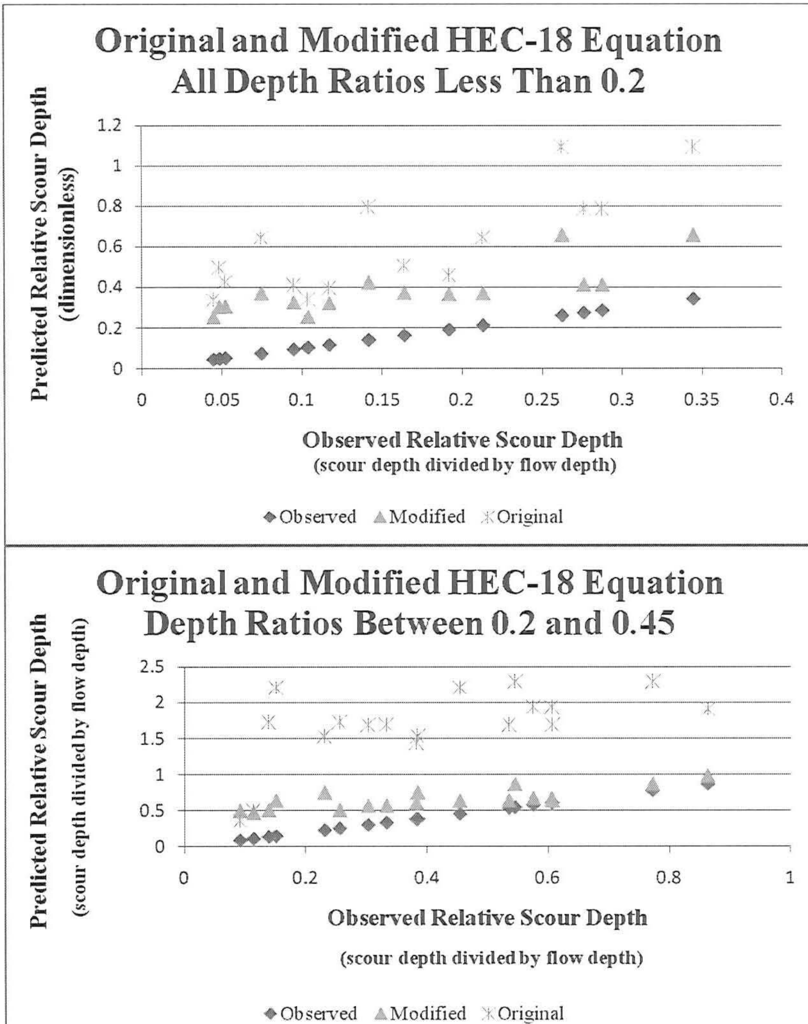

Figure 3: Comparisons between the original and modified HEC-18 local scour equation.

Table 4: Comparison of mean square error associated with the modified and original HEC-18 equation

	Mean Square Error from Validation Data Set	
	New Equation	Original HEC-18 Equation
Equation 2 lower	0.07	0.31
Equation 2 upper	0.10	2.18

Conclusions

Scour is a complex process that is difficult to describe with just a few easily obtained parameters. It is even more difficult to accurately describe scour with a single, one-size-fits-all equation. While this process showed stratifying the dataset and creating a family of equations can reduce error while maintaining safe design practices, the authors are mindful of the limited number of data points used in the construction of this model. For this reason, these authors recommend a continued effort to collect field-scale data especially across a wide range of expected conditions. With ample data, the family of equations can be expanded to cover the entire range of conditions currently covered by the HEC-18 local pier scour equation.

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